Multipropeller Whirl Flutter Stability Study using Component Mode Synthesis Element

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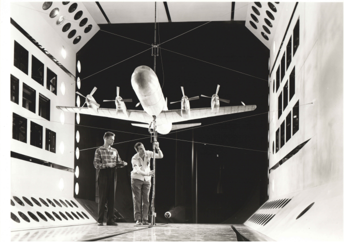
Overview

Whirl Flutter

This aeroelastic instability is caused by the propeller aerodynamics, which drives the airframe/pylon motion to become unstable[1].



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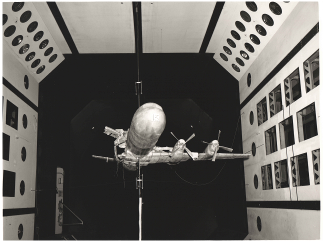


Electra

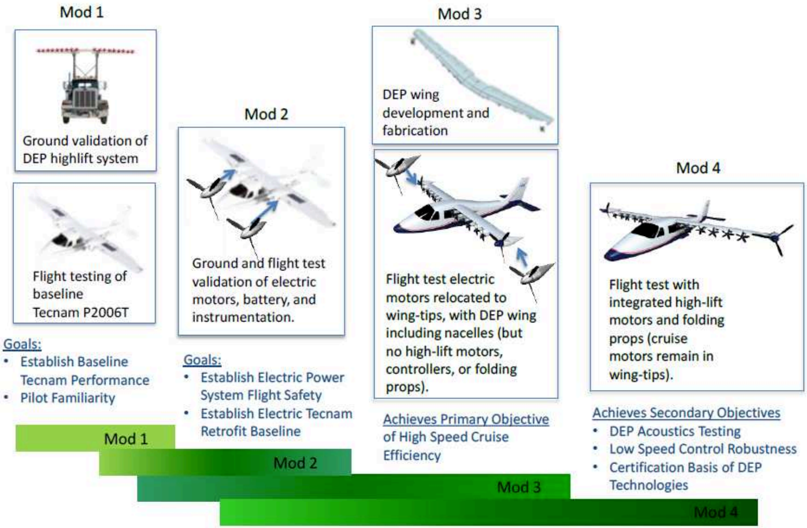
Fatal accidents of the Electra aircraft in the 1960s.
Structural failure that weakened the stiffness in the pylon mount.

[1] E. S. Taylor and K. A. Browne 1938J. Aero Sci. 6, no. 2,43. Vibration isolation of aircraft power plants.
[2] Houbolt,J.C., and ReedIII, W.H., Propeller-Nacelle Whirl Flutter, 1961.

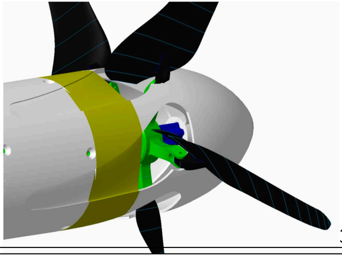
Literature Review

- E. S. Taylor and K. A. Browne 1938J. Aero Sci. 6, no. 2,43. Vibration isolation of aircraft power plants.
  - Propeller whirl flutter is discovered analytically.
- W. H. Reed III, Propeller-rotor whirl flutter: A state-of-the-art review, in Sound and Vibration, vol. 4, November 1966.
  - Theoretical and Experimental investigations and findings are presented on propeller whirl flutter.
- Johnson, W. Dynamics of Tilting Proprotor Aircraft in Cruise Flight. NASA TN D-7677, May 1974.
  - Derivation of a propeller whirl flutter solution considering the coupling of elastic wing modes with rigid and elastic proprotor blades.
- Hoover, C. B., and Shen, J., "Parametric Study of Propeller Whirl Flutter Stability with Full-Span Model of X-57 Maxwell Aircraft," Journal of Aircraft, vol. 55, 2018, pp. 2530–2537.
  - Parametric study of a semi and full-span model of the X-57 operating at a cruise condition of 8,000ft and 2250 RPM.

X-57 Maxwell Development



X-57 Maxwell



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Parameters

- All Electric
- 14 Propellers
  - 2 Large Outboard
  - 12 Small Inboard
- Thin, Highly Efficient Wings

Property	Value
Critical Takeoff Speed (kts)	58
Cruise Speed (kts)	150
Nacelle Length (ft)	1.9
Number of Blades	5
Propeller Diameter (ft)	1.9
Aircraft Weight (lbs)	$\approx 3,000$

[3] Litherland, B. L., Patterson, M. D., Derlaga, J. M., and Borer, N. K., "A Method for Designing Conforming Folding Propellers," 17th AIAA Aviation Technology, Integration, and Operations Conference, May 2017.

Outline

Multibody Dynamics Analysis: Dymore

Nonlinear Flexible Multibody Dynamics

- Element library includes rigid and deformable bodies and joint elements
- Deformable bodies are modeled as finite elements; beams and shells are geometrically exact
- Aerodynamics calculated using built-in lifting line theory or coupled with external aerodynamics code

Solution Method

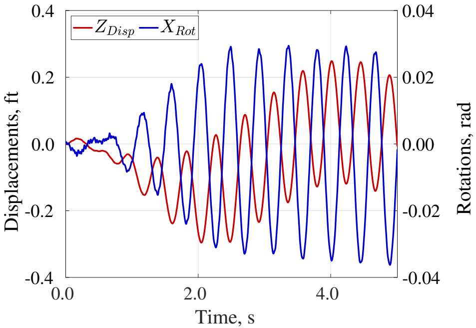
Use of Lagrangian multipliers to model constraints leads to system of differential-algebraic equations solved by robust time marching scheme

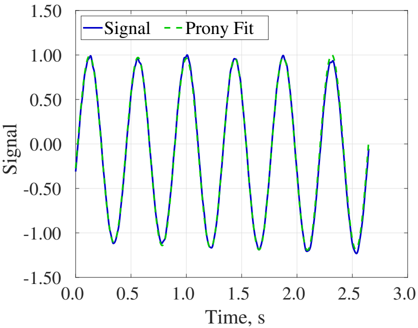
Model Excitation

Whirl flutter: a harmonic deadload is used to excite each individual mode and the transient response is recorded.

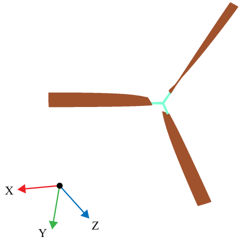
Prony Analysis

- Technique to measure the modal components within a given signal.
- Similar to using a Fourier Analysis but has the capability to estimate damping coefficients.
- This technique begins to break down when noise is present.

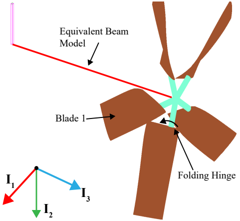




Dymore Propeller Models



(a) Dymore Tip Propeller Model



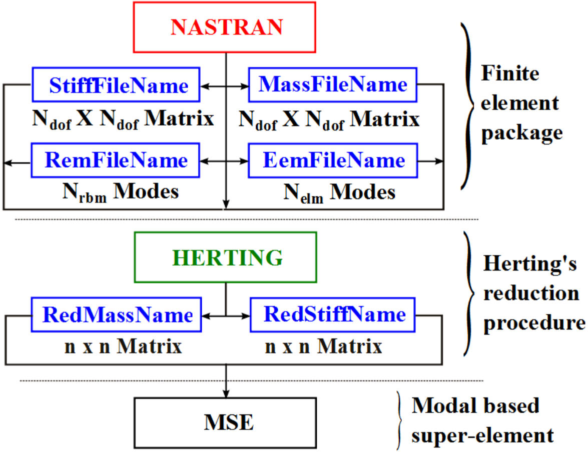
(b) Dymore High-Lift Propeller Model

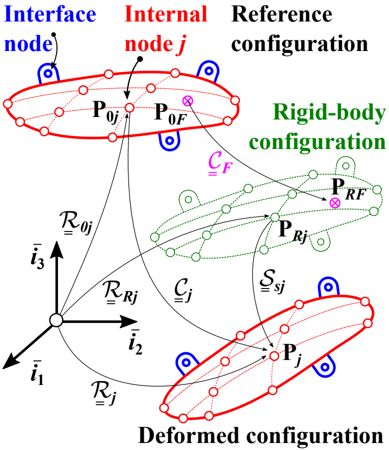
Structure

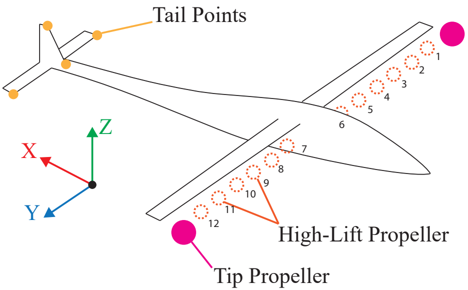
- Beams: blades.
- Rigid bodies: connection to MSE.
- Pitch revolute joint.
- No structural damping is included.

Aerodynamics

- Lifting line aerodynamics on rotor blades only.
- Uniform inflow model.


NASTRAN
StiffFileName
N_{dof} X N_{dof} Matrix
MassFileName
N_{dof} X N_{dof} Matrix
RemFileName
N_{rbm} Modes
EemFileName
N_{elm} Modes
Finite element package
HERTING
RedMassName
n x n Matrix
RedStiffName
n x n Matrix
Herting's reduction procedure
MSE
Modal based super-element


Interface node
Internal node j
Reference configuration
P_{0j}
P_{0F}
Rigid-body configuration
$\underline{\underline{\mathcal{C}}}_F$
P_{RF}
P_{Rj}
$\underline{\underline{\mathcal{R}}}_{0j}$
$\bar{i}_3$
$\underline{\underline{\mathcal{R}}}_{Rj}$
$\underline{\underline{\mathcal{C}}}_j$
$\underline{\underline{\mathcal{S}}}_{sj}$
$\bar{i}_2$
$\bar{i}_1$
P_j
$\underline{\underline{\mathcal{R}}}_j$
Deformed configuration



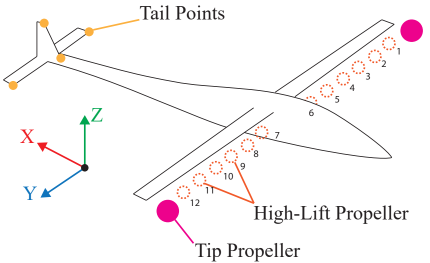
- Reduced order modeling techniques provide smaller representations of large complex mechanical systems
- Dymore relies on reduced matrices from the "mode-acceleration method"
- Interface and internal nodes are used with the internal nodes through modal-reduction
- No structural damping is included

Mode	7	8	9	10	11	12	13	14	15
NASTRAN	3.04	5.67	6.97	9.92	11.44	12.05	13.70	14.16	15.61
MSE	3.05	5.72	7.06	10.01	11.50	12.37	13.96	14.45	16.06

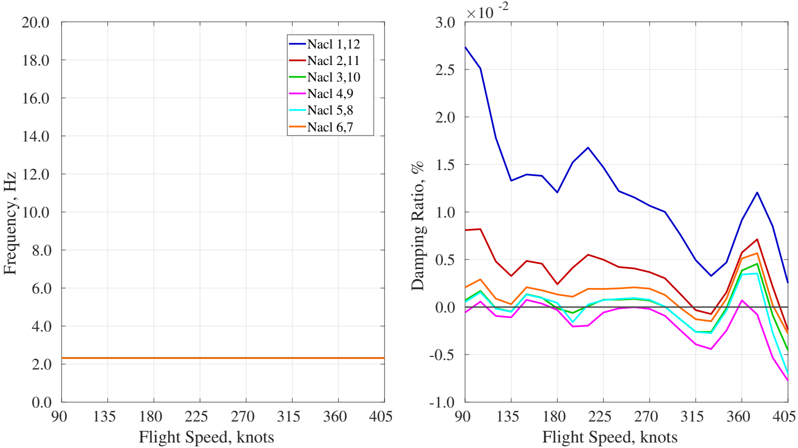
Outline

High-Lift Propeller Whirl Flutter Sensitivity Study

- High-Lift Propeller pairs are simulated with increasing flight speed.
- A constant 4400 RPM is assumed for this study.
- A constant altitude of 2400 ft is assumed for this study.
- Like propellers are modeled on a full-span MSE model of the X-57.
  - Rotor pairs will be 1 and 12, 2 and 11, so on.

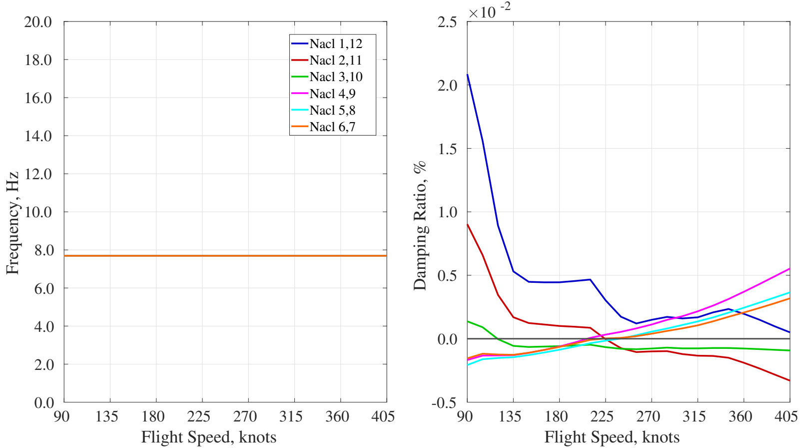


Frequency and Damping of Symmetric Out-of-Plane Bending Mode



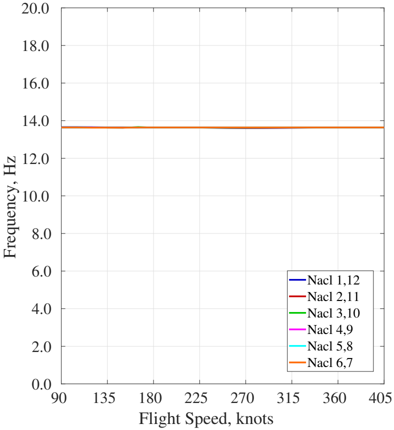
All of the damping is very low. The nacelle pairs at grid 4 and 9 have a consistently unstable response for the velocity range simulated. No structural damping is included.

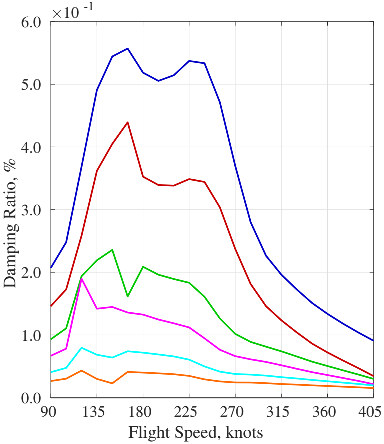
Frequency and Damping of Symmetric Inplane Bending Mode



The outboard pairs have the highest damping at low speed. The inboard pairs have a gradual increase in damping with flight speed.

Frequency and Damping of Symmetric Torsion Mode





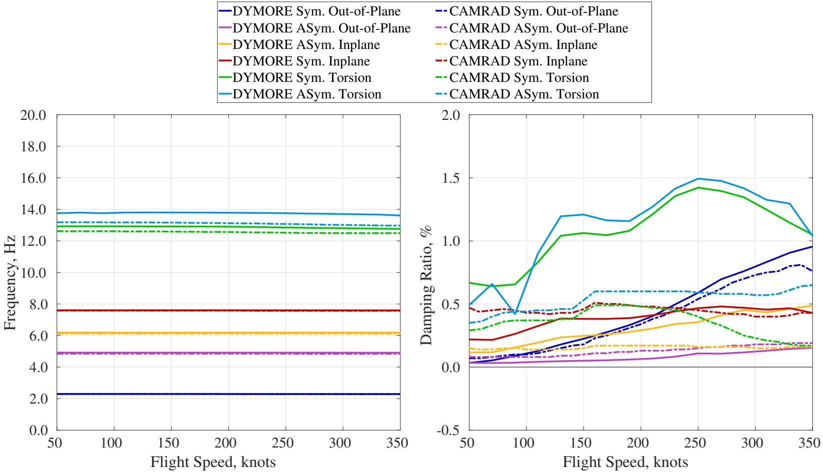
The response to torsional stability is heavily influenced by propeller location. High-lift propellers moving outboard from the fuselage have greater damping.

Outline

X-57 Mod 4 Configuration - All 14 Propeller Simulation

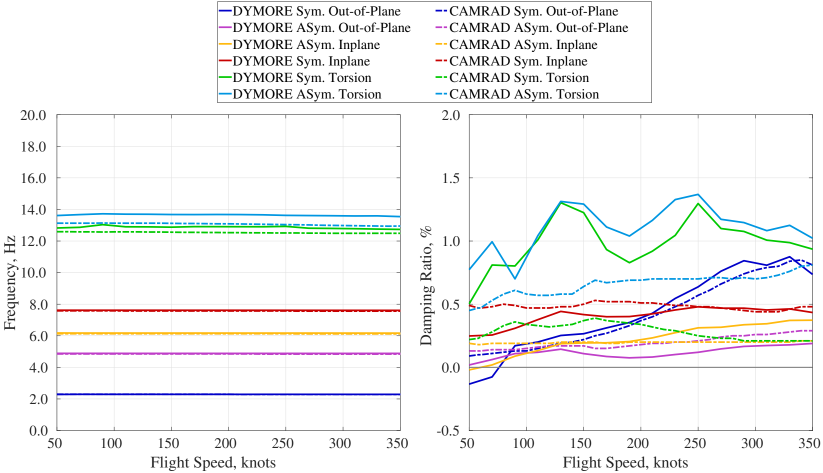
- The Mod 4 X-57 Maxwell configuration is fully populated with 14 propellers.
- Additional mass is added to the high-lift propeller hub, tip propeller hub, and tip propeller motor location.
  - This added mass is for blade mass, extra mass at the hub, and motor masses taken out of the FEM.
- All cases are run at 8,000 ft.
- The tip propeller is held to 2700 RPM and trimmed to a zero thrust condition.
- Overspeed cases are 10% higher RPM from the operational maximum, high-lift propeller 5940 RPM.
- CAMRAD is using a rigid tip propeller blade.

Case 1: 2700 Tip Propeller RPM, 0 High-Lift Propeller RPM



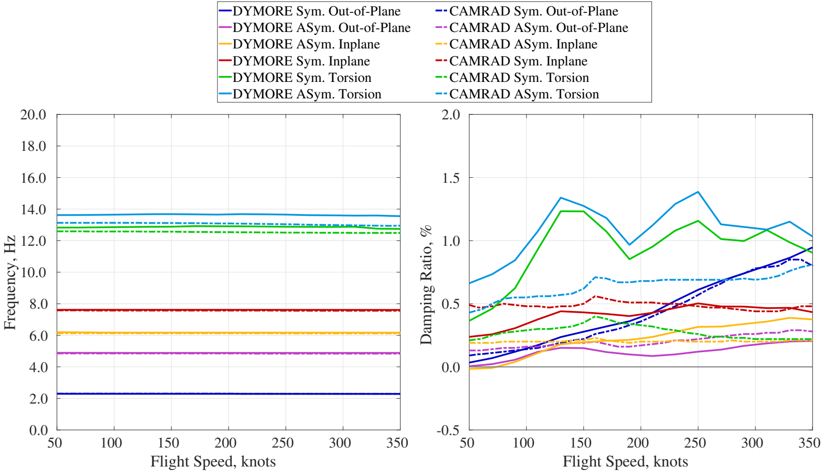
Dymore and CAMRAD have good agreement for the symmetric out of plane bending mode. Dymore estimates greater damping for the antisymmetric modes.

Case 2: 2700 Tip Propeller RPM, Scheduled High-Lift Propeller RPM



At low speed, the symmetric out of plane is unstable and the antisymmetric inplane mode is marginally unstable at 50 knots.

Case 3: 2700 Tip Propeller RPM, Overspeed High-Lift Propeller RPM



The antisymmetric inplane mode is marginally unstable to 70 knots flight speed.

Summary and Conclusion

- Multibody dynamics codes, Dymore and CAMRAD, are used to estimate the propeller whirl-flutter stability of the NASA X-57 Maxwell.
- A modal-super-element (MSE) is used in Dymore to model the structural dynamics of the X-57 Maxwell fuselage/wing/empennage.
- A parametric study investigates the influence of high-lift propeller pair location on whirl-flutter stability
  - The propeller pair located closest to the wingtips, in general, have the greatest contribution, albeit the contribution is small due to the small size of the propellers.
- The aircraft is simulated with all 14 propellers present and assumes constant tip propeller RPM while varying the high-lift propeller RPM and subjecting the vehicle to increasing flight speeds at constant altitude.
  - Symmetric wing out-of-plane bending is captured well between Dymore and CAMRAD with the high-lift propellers set to zero and overspeed RPM conditions.
  - Dymore predicts marginal low-speed instability with the high-lift propellers in operation (analytical models include no structural damping).

Acknowledgments

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